# Modularity

The material for this lecture is drawn, in part, from
*The Practice of Programming* (Kernighan & Pike) Chapter 4

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## Goals of this Lecture

- Help you learn:
  - How to create high quality modules in C
- Why?
  - Abstraction is a powerful (the only?) technique available for understanding large, complex systems
  - A power programmer knows how to find the abstractions in a large program
  - A power programmer knows how to convey a large program's abstractions via its modularity

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## Module Design Heuristics

- We propose 7 module design heuristics
- Let' s consider one at a time…

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## Interface/Implementation Separation

(1) A well-designed module separates interface and implementation

- Why?
  - Hides implementation details from clients
    - Thus facilitating abstraction
  - Allows separate compilation of each implementation
    - Thus allowing partial builds

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## Interface Example 1

- Stack: A stack whose items are strings
  - Data structure
    - Linked list
  - Algorithms
    - **new**: Create a new Stack object and return it (or NULL if not enough memory)
    - **free**: Free the given Stack object
    - **push**: Push the given string onto the given Stack object and return 1 (or 0 if not enough memory)
    - **top**: Return the top item of the given Stack object
    - **pop**: Pop a string from the given Stack object and discard it
    - **isEmpty**: Return 1 if the given Stack object is empty, 0 otherwise



## Interfaces Example 1

- Stack (version 1)

```
/* stack.c */

struct Node {
   const char *item;
   struct Node *next;
};
struct Stack {
   struct Node *first;
};

struct Stack *Stack_new(void) {…}
void  Stack_free(struct Stack *s) {…}
int   Stack_push(struct Stack *s, const char *item) {…}
char *Stack_top(struct Stack *s) {…}
void  Stack_pop(struct Stack *s) {…}
int   Stack_isEmpty(struct Stack *s) {…}
```

```
/* client.c */

#include "stack.c"

/* Use the functions
defined in stack.c. */
```

- Stack module consists of one file (stack.c); no interface
- Problem: Change stack.c => must rebuild stack.c ***and client***
- Problem: Client "sees" Stack function definitions; poor abstraction



## Interfaces Example 1

- Stack (version 2)

```
/* stack.h */

struct Node {
   const char *item;
   struct Node *next;
};
struct Stack {
   struct Node *first;
};

struct Stack *Stack_new(void);
void  Stack_free(struct Stack *s);
int   Stack_push(struct Stack *s, const char *item);
char *Stack_top(struct Stack *s);
void  Stack_pop(struct Stack *s);
int   Stack_isEmpty(struct Stack *s);
```

- Stack module consists of two files:
  (1) stack.h (the interface) declares functions and defines data structures



## Interfaces Example 1

- Stack (version 2)

```
/* stack.c */

#include "stack.h"

struct Stack *Stack_new(void) {…}
void  Stack_free(struct Stack *s) {…}
int   Stack_push(struct Stack *s, const char *item) {…}
char *Stack_top(struct Stack *s) {…}
void  Stack_pop(struct Stack *s) {…}
int   Stack_isEmpty(struct Stack *s) {…}
```

(2) stack.c (the implementation) defines functions
- #includes stack.h so that:
  - Compiler can check consistency of function declarations and definitions
  - Functions have access to data structures

## Interfaces Example 1

- Stack (version 2)

```
/* client.c */

#include "stack.h"

/* Use the functions declared in stack.h. */
```

- Client #includes only the interface
- Change stack.c => must rebuild stack.c, ***but not the client***
- Client does not "see" Stack function definitions; better abstraction



## Interface Example 2

- string (also recall Str from Assignment 2)

```
/* string.h */

size_t strlen(const char *s);
char   *strcpy(char *dest, const char *src);
char   *strncpy(char *dest, const char *src, size_t n);
char   *strcat(char *dest, const char *src);
char   *strncat(char *dest, const char *src, size_t n);
int     strcmp(const char *s, const char *t);
int     strncmp(const char *s, const char *t, size_t n);
char   *strstr(const char *haystack, const char *needle);
…
```



## Interface Example 3

- stdio (from C90, vastly simplified)

```
/* stdio.h */

struct FILE {
   int cnt;    /* characters left */
   char *ptr;  /* next character position */
   char *base; /* location of buffer */
   int flag;   /* mode of file access */
   int fd;     /* file descriptor */
};

#define OPEN_MAX 20
FILE _iob[OPEN_MAX];

#define stdin  (&_iob[0]);
#define stdout (&_iob[1]);
#define stderr (&_iob[2]);
…
```

Don't be concerned with details



## Interface Example 3

- stdio (cont.)

```
…
FILE *fopen(const char *filename, const char *mode);
int   fclose(FILE *f);
int   fflush(FILE *f);

int   fgetc(FILE *f);
int   getc(FILE *f);
int   getchar(void);

int   putc(int c, FILE *f);
int   putchar(int c);

int   fscanf(FILE *f, const char *format, …);
int   scanf(const char *format, …);

int   fprintf(FILE *f, const char *format, …);
int   printf(const char *format, …);
…
```

## Encapsulation

(2) A well-designed module encapsulates data

- An interface should hide implementation details
- A module should use its functions to encapsulate its data
  - Should not allow clients to manipulate the data directly
  - Only through the functions that constitute the module's interface

- Why?
  - **Clarity**: Encourages abstraction
  - **Security**: Clients cannot corrupt object by changing its data in unintended ways
  - **Flexibility**: Allows implementation to change the data structure without affecting clients



## Encapsulation Example 1

- Stack (version 1)

```
/* stack.h */

struct Node {
   const char *item;
   struct Node *next;
};
struct Stack {
   struct Node *first;
};

struct Stack *Stack_new(void);
void  Stack_free(struct Stack *s);
void  Stack_push(struct Stack *s, const char *item);
char *Stack_top(struct Stack *s);
void  Stack_pop(struct Stack *s);
int   Stack_isEmpty(struct Stack *s);
```

Structure type definitions in .h file

- That's bad
- Interface reveals how Stack object is implemented (e.g., as a linked list)
- Client can access/change data directly; could corrupt object



## Encapsulation Example 1

- Stack (version 2)

```
/* stack.h */

struct Stack;

struct Stack *Stack_new(void);
void  Stack_free(struct Stack *s);
void  Stack_push(struct Stack *s, const char *item);
char *Stack_top(struct Stack *s);
void  Stack_pop(struct Stack *s);
int   Stack_isEmpty(struct Stack *s);
```

Place ***declaration*** of struct Stack in interface; move ***definition*** to Implementation.
Clients need not know about definition.
No struct Node in stack.h

- That's better
- Interface does not reveal how Stack object is implemented
- Client cannot access data directly



## Encapsulation Example 1

- Stack (version 3)

```
/* stack.h */

typedef struct Stack *Stack_T;

Stack_T Stack_new(void);
void  Stack_free(Stack_T s);
void  Stack_push(Stack_T s, const char *item);
char *Stack_top(Stack_T s);
void  Stack_pop(Stack_T s);
int   Stack_isEmpty(Stack_T s);
```

Opaque pointer

- That's better still
- Interface provides "Stack_T" abbreviation for client
- Interface encourages client to view a Stack as an object, not as a (pointer to a) structure
- Client still cannot access data directly; data are "opaque" to client

## Encapsulation Example 2

- string
  - "Stateless" module
  - Has no state to encapsulate

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## Encapsulation Example 3

- stdio

```
/* stdio.h */

struct FILE {
    int cnt;     /* characters left */
    char *ptr;   /* next character position */
    char *base;  /* location of buffer */
    int flag;    /* mode of file access */
    int fd;      /* file descriptor */
};
…
```

Structure type definition in .h file

  - Violates the heuristic
  - Programmers can access data directly
    - Can corrupt the FILE object
    - Can write non-portable code
  - But let's make excuses for poor stdio …
    - The functions are well documented
    - Few programmers examine stdio.h
    - Few programmers are tempted to access the data directly

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## Resource Management

(3) A well-designed module manages resources consistently
- A module should free a resource if and only if the module has allocated that resource
- Examples
  - Object allocates memory <=> object frees memory
  - Object opens file <=> object closes file

- Why?
  - Error-prone to allocate and free resources at different levels

What if module allocates memory and nobody frees it?

What if module frees memory that nobody has allocated?

Other resources then memory?

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## Resources Example 1

- Stack: Who allocates and frees the strings?
  - Reasonable options:
    (1) Client allocates and frees strings
    - `Stack_push()` does not create copy of given string
    - `Stack_pop()` does not free the popped string
    - `Stack_free()` does not free remaining strings

    (2) Stack object allocates and frees strings
    - `Stack_push()` creates copy of given string
    - `Stack_pop()` frees the popped string
    - `Stack_free()` frees all remaining strings
  - Our choice: (1)

Advantages/ disadvantages?

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## Resources Examples 2, 3

- string
  - Stateless module
  - Has no resources to manage
- stdio
  - **`fopen()`** allocates memory, uses file descriptor
  - **`fclose()`** frees memory, releases file descriptor

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## Symbol Table Aside

- Consider SymTable (from Assignment 3)…
- Who allocates and frees the key strings?
  - Reasonable options:
    - (1) Client allocates and frees strings
      - **`SymTable_put()`** does not create copy of given string
      - **`SymTable_remove()`** does not free the string
      - **`SymTable_free()`** does not free remaining strings
    - (2) SymTable object allocates and frees strings
      - **`SymTable_put()`** creates copy of given string
      - **`SymTable_remove()`** frees the string
      - **`SymTable_free()`** frees all remaining strings
  - Our choice: (2)

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## Passing Resource Ownership

- Passing resource ownership
  - Should note violations of the heuristic in function comments

```
/* somefile.h */

…

void *f(void);
/* …
   This function allocates memory for
   the returned object.  You (the caller)
   own that memory, and so are responsible
   for freeing it when you no longer
   need it. */

…
```

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## Consistency

### (4) A well-designed module is consistent

- A function's name should indicate its module
  - Facilitates maintenance programming; programmer can find functions more quickly
  - Reduces likelihood of name collisions (from different programmers, different software vendors, etc.)
- A module's functions should use a consistent parameter order
  - Facilitates writing client code

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## Consistency Examples

- Stack
  - (+) Each function name begins with "Stack_"
  - (+) First parameter identifies Stack object
- string
  - (+) Each function name begins with "str"
  - (+) Destination string parameter comes before source string parameter; mimics assignment

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## Consistency Examples (cont.)

- stdio

```
…
FILE *fopen(const char *filename, const char *mode);
int   fclose(FILE *f);
int   fflush(FILE *f);

int   fgetc(FILE *f);
int   getc(FILE *f);
int   getchar(void);

int   putc(int c, FILE *f);
int   putchar(int c);

int   fscanf(FILE *f, const char *format, …);
int   scanf(const char *format, …);

int   fprintf(FILE *f, const char *format, …);
int   printf(const char *format, …);
…
```

Are function names consistent?

Is parameter order consistent?

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## Minimization

### (5) A well-designed module has a minimal interface

- Function declaration should be in a module's interface if and only if:
  - The function is **necessary** to make objects complete, or
  - The function is **convenient** for many clients
- Why?
  - More functions => higher learning costs, higher maintenance costs

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## Minimization Example 1

- Stack

```
/* stack.h */

typedef struct Stack *Stack_T ;

Stack_T Stack_new(void);
void  Stack_free(Stack_T s);
void  Stack_push(Stack_T s, const char *item);
char *Stack_top(Stack_T s);
void  Stack_pop(Stack_T s);
int   Stack_isEmpty(Stack_T s);
```

Should any functions be eliminated?

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## Minimization Example 1

- Another Stack function?

```
void Stack_clear(Stack_T s);
```

  - Pops all items from the Stack object

Should the Stack ADT define Stack_clear()?



## Minimization Example 2

- string

```
/* string.h */

size_t strlen(const char *s);
char   *strcpy(char *dest, const char *src);
char   *strncpy(char *dest, const char *src, size_t n);
char   *strcat(char *dest, const char *src);
char   *strncat(char *dest, const char *src, size_t n);
int     strcmp(const char *s, const char *t);
int     strncmp(const char *s, const char *t, size_t n);
char   *strstr(const char *haystack, const char *needle);
…
```

Should any functions be eliminated?



## Minimization Example 3

- stdio

```
…
FILE *fopen(const char *filename, const char *mode);
int   fclose(FILE *f);
int   fflush(FILE *f);

int   fgetc(FILE *f);
int   getc(FILE *f);
int   getchar(void);

int   putc(int c, FILE *f);
int   putchar(int c);

int   fscanf(FILE *f, const char *format, …);
int   scanf(const char *format, …);

int   fprintf(FILE *f, const char *format, …);
int   printf(const char *format, …);
…
```

Should any functions be eliminated?



## SymTable Aside

- Consider SymTable (from Assignment 3)

  - Declares `SymTable_get()` in interface
  - Declares `SymTable_contains()` in interface

Should SymTable_contains() be eliminated?

## SymTable Aside (cont.)

- Consider SymTable (from Assignment 3)
  - Defines `SymTable_hash()` in implementation

> Should SymTable_hash() be declared in interface?

- Incidentally: In C any function should be either:
  - **Non-static**, and **declared** in the interface
  - **Static**, and **not declared** in the interface

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## Error Detection/Handling/Reporting

(6) A well-designed module detects and handles/ reports errors

- A module should:
  - **Detect** errors
  - **Handle** errors if it can; otherwise…
  - **Report** errors to its clients
    - A module often cannot assume what error-handling action its clients prefer

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## Detecting and Handling Errors in C

- C options for **detecting** errors
  - `if` statement
  - `assert` macro
- C options for **handling** errors
  - Print message to stderr
    - Impossible in many embedded applications
  - Recover and proceed
    - Sometimes impossible
  - Abort process
    - Often undesirable

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## Reporting Errors in C

- C options for **reporting** errors to client
  - Set **global variable**?
    - Easy for client to forget to check
    - Bad for multi-threaded programming
  - Use **function return value**?
    - Awkward if return value has some other natural purpose
  - Use extra **call-by-reference parameter**?
    - Awkward for client; must pass additional parameter
  - Call `assert` **macro**?
    - Terminates the entire program
- No option is ideal

> What additional option does Java provide?

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## User Errors

Our recommendation: Distinguish between…

(1) **User** errors

- Errors made by human user of the program
- Errors that "could happen"

- Example: Bad data in stdin
- Example: Bad value of command-line argument

- Use `if` statement to detect
- Handle immediately if possible, or …
- Report to client via return value or call-by-reference parameter

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## Programmer Errors

(2) **Programmer** errors

- Errors made by a programmer
- Errors that "should never happen"

- Example: `int` parameter should not be negative, but is
- Example: pointer parameter should not be `NULL`, but is

- Use `assert` to detect and handle

- The distinction sometimes is unclear
  - Example: Write to file fails because disk is full

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## Error Handling Example 1

- Stack

```
/* stack.c */
…
int Stack_push(Stack_T s, const char *item) {
   struct Node *p;
   assert(s != NULL);
   p = (struct Node*)malloc(sizeof(struct Node));
   if (p == NULL) return 0;
   p->item = item;
   p->next = s->first;
   s->first = p;
   return 1;
}
```

- Invalid parameter is **programmer** error
  - Should never happen
  - Detect and handle via `assert`
- Memory allocation failure is **user** error
  - Could happen (huge data set and/or small computer)
  - Detect via `if`; report to client via return value

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## Error Handling Examples 2, 3

- string
  - No error detection or handling/reporting
  - Example: NULL parameter to `strlen()` => probable seg fault
- stdio
  - Detects bad input
  - Uses function return values to report failure
    - Note awkwardness of `scanf()`
  - Sets global variable `errno` to indicate reason for failure

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## Establishing Contracts

- (7) A well-designed module establishes contracts
  - A module should establish contracts with its clients
  - Contracts should describe each function's interface, esp:
    - Meanings of parameters
    - What the function does
    - Meaning of return value
    - Side effects
- Why?
  - Facilitates cooperation between multiple programmers
  - Assigns blame to contract violators
    - If your functions have precise contracts and implement them correctly, then the bug must be in someone else's code

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## Establishing Contracts in C

- Our recommendation…
- In C, establish contracts via comments in module interface

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## Establishing Contracts Example

- Stack

```
/* stack.h */
…
/* Push item onto s.  Return 1 (TRUE)
   if successful, or 0 (FALSE) if
   insufficient memory is available. */
int Stack_push(Stack_T s, const char *item);
…
```

- Comment defines contract:
  - Meaning of function's parameters
    - s is the stack to be affected; item is the item to be pushed
  - What the function does
    - Push item onto s
  - Meaning of return value
    - Indicates success/failure
  - Side effects
    - (None, by default)

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## Summary

- A well-designed module:
  - (1) Separates interface and implementation
  - (2) Encapsulates data
  - (3) Manages resources consistently
  - (4) Is consistent
  - (5) Has a minimal interface
  - (6) Detects and handles/reports errors
  - (7) Establishes contracts

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## Appendix

Two additional, more advanced heuristics

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## Strong Cohesion

(8) A well-designed module has strong cohesion
- A module's functions should be strongly related to each other

- Why?
  - Strong cohesion facilitates abstraction

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## Strong Cohesion Examples

- Stack
  - (+) All functions are related to the encapsulated data
- string
  - (+) Most functions are related to string handling
  - (-) Some functions are not related to string handling
    - `memcpy()`, `memmove()`, `memcmp()`, `memchr()`, `memset()`
  - (+) But those functions are similar to string-handling functions
- stdio
  - (+) Most functions are related to I/O
  - (-) Some functions don't do I/O
    - `sprintf()`, `sscanf()`
  - (+) But those functions are similar to I/O functions

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## Weak Coupling

(9) A well-designed module has weak coupling
- Module should be weakly connected to other modules in program
- Interaction within modules should be more intense than interaction among modules

- Why? Theoretical: easier to modify
  - Maintenance: Weak coupling makes program easier to modify
  - Reuse: Weak coupling facilitates reuse of modules
- Why? Empirical: fewer bugs
  - Empirically, modules that are weakly coupled have fewer bugs

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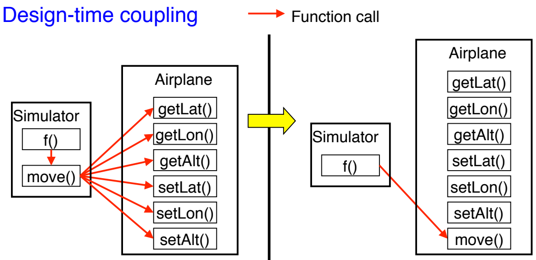
## Weak Coupling Examples

- Design-time coupling




- Client module calls many functions in my module
- Strong design-time coupling

- Client module calls few functions in my module
- Weak design-time coupling

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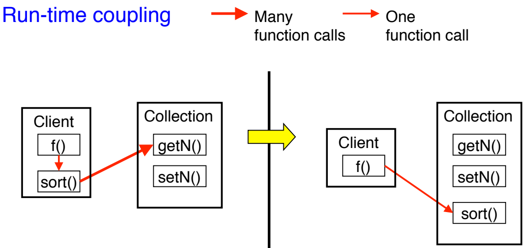
## Weak Coupling Examples (cont.)

- Run-time coupling




- Client module makes many calls to my module
- Strong run-time coupling

- Client module makes few calls to my module
- Weak run-time coupling

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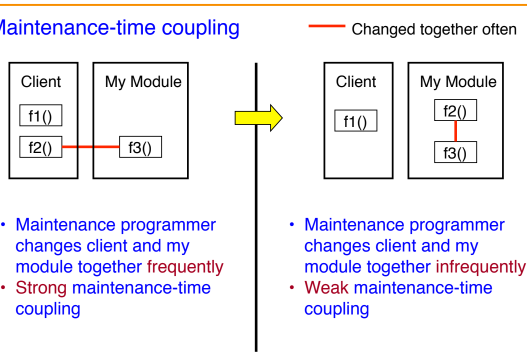
## Weak Coupling Examples (cont.)

- Maintenance-time coupling




- Maintenance programmer changes client and my module together frequently
- Strong maintenance-time coupling

- Maintenance programmer changes client and my module together infrequently
- Weak maintenance-time coupling

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## Achieving Weak Coupling

- Achieving weak coupling could involve moving code:
  - From clients to my module (shown)
  - From my module to clients (not shown)
  - From clients and my module to a new module (not shown)

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## Summary

- A well-designed module:
  - (1) Separates interface and implementation
  - (2) Encapsulates data
  - (3) Manages resources consistently
  - (4) Is consistent
  - (5) Has a minimal interface
  - (6) Detects and handles/reports errors
  - (7) Establishes contracts
  - **(8) Has strong cohesion**
  - **(9) Has weak coupling**

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